Evaluation of AWG Technology

Draft Project Plan

Summary

Previous, independent assessment by the US Army's Tank Automotive Research Development and Engineering Center (TARDEC) program found that Atmospheric Water Generators are a relatively inefficient means of producing clean water, even relative to energy intensive approaches such as reverse osmosis. Quality of the produced water generally met EPA standards for drinking water, although the occurrence of pathogens known to grow on wetted surfaces and condensate (i.e., *Legionella, Mycobacterium*) was not evaluated.

Commercial producers of AWG system exist, including some who report significantly improved efficiencies.

EPA proposes to collaborate with interested vendors via CRADAs to conduct assessment of their technologies focused on 1) testing microbiological water quality during long term operation, and 2) developing life cycle costs to perform quantitative cost/benefit analysis of AWG use for EPA relevant scenarios.

This work leverages EPA expertise related to opportunistic pathogens (i.e., *Legionella, Mycobacterium*), water reuse via air conditioning condensate recovery, and life cycle assessment of alternative approaches to water systems.

EPA's existing memorandum of understanding (MOU) with DOD can facilitate cooperative evaluation of advances in AWG technology; DOD is planning to test a specific new technology beginning in 2018.

Introduction:

Active Atmospheric water generators (AWG's) produce potable water from ambient air. These units range from home based units that can produce 1 to 20 liters per day to commercial scale units capable of 1,000 to >10000 liters per day. Water production rates are highly dependent on the amount of water vapor (i.e., humidity) and temperature of air.

The most commonly used AWG systems employ condenser and cooling coil technology to pull moisture from the air in the same way as a household dehumidifier. Significant quantities of energy are required to operate the condenser and fan systems, such that the process has been characterized as "trading water for oil." However, recent technological advancements have substantially improved the fuel-water ratio, even in traditional condenser-based units, which increases the viability of these systems for improving the Nation's water infrastructure. Emerging technologies, such as solar-powered or desiccant based systems which pull water from the air using "wet" hygroscopic substances, could offer more efficient or even energy-neutral avenues for future AWG development/ deployment.

At least 70 companies produce AWG devices exist worldwide; and 72 expired, filed, or issued patents exist for AWG technology. For comparison, a summary of Water-Gen and one American AWG company, Sky H2O, is provided below. SkyH20 provided a "shark tank" presentation at WaterVent 2017 on May 4 in Philadelphia that EPA staff participated at. These two are illustrative examples only.

- Water-Gen is an Israeli company producing modular and backpack-transportable water purification and AWG systems. Water-Gen claims its large-scale AWG unit produces 6000 liters per day of drinking water at 350 Wh/L at conditions of 26.7 ° C and 60% RH. Water-Gen claims its devices can produce drinking water at efficiencies of between 3.3-4.5 L/Kw, compared to the claimed "market average" of 1.2-2 L/Kw; at a cost of $20/1000L at $0.08/kWh. The large-scale unit is intended to provide rooftop AWG for drinking water, allowing public water supply to be used for non-drinking uses such as landscaping.
- Sky H2O is an American company producing a modular AWG system built into a shipping crate. Sky H2O claims it can produce 10,5000 L/day of drinking water meeting World Health Organization (WHO) standards, at efficiencies of 0.29 kWh/L at 80% RH; at a cost of $40/1000L at $0.06/kWh. Sky H2O claims to be the only AWG manufacturer that has completed third-party evaluation of their product performance claims.

EPA has explored the feasibility of AWG systems for different scenarios in recent years. For instance, OLEM examined the application of AWG's to supplement or provide drinking water during Superfund response actions. OLEM found the AWG technology reviewed to be relatively energy intensive. ranging from .31-.63 kWh (at a cost of $0.04 to $0.08) to produce a single liter of water. By comparison, the cost of water from a public water supply is about $0.003 per liter of water. However, OLEM did note that these figures still make AWG water production lower cost than providing bottled water in an emergency or alternative water supply scenario where public supply is not available. A market scan by OW reached similar conclusions, characterizing current AWG technology primarily as a "last resort option" where surface or groundwater treatment is not economically or technologically feasible.

There have been few rigorous, long-term, third-party evaluations of AWG technology in the US. In 2006-2007, the US Army's Tank Automotive Research Development and Engineering Center (TARDEC) program, tested a commercial-off-the-shelf hybrid desiccant and condenser-based unit at Aberdeen Proving Ground Maryland. TARDEC procured and tested a single, diesel-powered prototype MesoSystems (part of Fisher Scientific) *SkyPure Water Generator from Air* unit at Aberdeen Proving Ground, Maryland. Both field and controlled laboratory tests were performed. The TARDEC team recorded lab-controlled and field-based water quality, water production and fuel consumption measurements for the SkyPure unit over several different periods and under different operating conditions from July-2006 to January 2007.

The Sky Pure system is a hybrid desiccant and condenser based unit which first employs a "desiccant wheel" to separate moisture and moisture-rich air from dry air. Dry air is exhausted and the remaining moist air is then sent via a heat exchanger to an auxiliary condenser/ coil cooling system where the residual water is extracted. The system uses a single air mover fan, which decreases energy needed for water production. Biostone treatment filters are included in the water stream, but the unit does not have a chlorine injection system. The unit is roughly the same size as a household chest freezer, fitting on a double length shipping pallet. The unit runs quietly enough with panels closed to negate the need for hearing protection.

The objectives of the water production and fuel consumption tests were to:

a) To evaluate the effects of a range of temperature and humidity conditions on the performance of the system.
b) To determine if the water generator supplies water at required production rates at different temperature and humidity levels.
c) To determine the fuel consumption rates of the system at different temperature and humidity levels.

Effects of temperature and humidity conditions on fuel consumption and water production

These tests were performed in a climatic chamber to standards MIL-STD-810F (ref 12), Test Methods 501.4 and 502.3, and Standing Operating Procedure (SOP) 385-4060 (ref 13). Exhaust tubes connected to the diesel engine and fuel burner exhausted pipes were directed external to the chamber. Chamber air temperature and relative humidity (RH) were monitored and recorded along with fuel consumption (volumetric and by weight). The results of this analysis are displayed in Table 1 below.

*Table 1. Summary of Environmental Chamber Test Water Production and Fuel Consumption**

DATE, 06	AUXILIARY COOLER	AVERAGE TEMPERATURE °C	AVERAGE TEMPERATURE °F	AVERAGE % RH	AVERAGE ABSOLUTE HUMIDITY, g/kg	WATER PRODUCTION mL/hr	WATER PRODUCTION gal./hr	FUEL CONSUMPTION mL/hr	FUEL CONSUMPTION gal./hr	WATER/ FUEL RATIO	REMARKS
24 Jul	Off	6.2	43.2	75.9	4.46	7,979	2.11	1976	0.52	4.06	
26 Jul	Off	24.5	76.1	50.1	9.61	6,899	1.82	1686	.45	4.04	Design point condition.
27 Jul	Off	35.3	95.5	49.6	17.90	5,678	1.50	1574	.42	3.57	
	On	35.1	95.2	49.4	17.66	6,493	1.72	1522	.40	4.30	
28 Jul	Off	48.9	120.0	39.9	30.00	2,751	0.73	1390	.37	1.97	
	On	49.5	121.1	39.5	30.65	2,630	0.70	1424	.38	1.84	
29 Jul	Off	48.4	119.2	26.8	19.39	1,230	0.33	1516	.40	0.78	Daily average for fuel.
	On	49.4	121.0	26.5	20.18	1,093	0.29				
30 Jul	Off	24.5	76.2	61.1	11.79	7,498	1.98	2020	.53	3.73	
	On	23.7	74.6	60.1	10.98	8,511	2.25	1936	.51	4.41	
31 Jul	Off	32.1	89.8	93.1	28.63	8,060	2.13	1728	.46	4.63	
	On	32.7	90.9	94.4	30.11	10,449	2.76	1618	.43	6.42	
1 Aug	Off	15.9	60.6	43.7	4.88	7,560	2.00	1719	.45	4.54	Daily average for fuel.
	On	16.1	61.0	43.3	4.91	7,908	2.09				
2 Aug	On	25.0	77.0	48.7	9.62	7,346	1.94	1848	.49	3.96	Design point condition.
3 Aug	Off	21.9	71.4	40.4	6.58	6,163	1.63	2005	.53	3.32	Daily average for fuel.
	On	21.1	69.9	39.9	6.17	7,137	1.89				
4 Aug	Off	8.5	47.3	50.9	3.49	7,600	2.01	1977	.52	3.90	Daily average for fuel.
	On	8.7	47.7	51.1	3.55	7,753	2.05				

*Courtesy of TARDEC: ATEC PROJECT NO. 2006-DT-ATC-FCSOS-D1766. REPORT NO. ATC-9343

Water production ranged from a low of 0.29 gal/ hr to a high of 2.76 gal/ hour. Under system design conditions (77 degrees F/ 50%RH)m, using the auxiliary cooling system increases water production by about 6.5% (1.94 vs 1.82 gal/hr). Interestingly, water production was not found to be linear with humidity and temperature, although this could be due to moisture collecting in the flexible air mover ducts – a potential design flaw which was noted by TARDEC.

Fuel consumption and water production at different temperature and RH values can be represented simultaneously with a water/ fuel ratio, which is also displayed in Table 1. Fuel consumption was fairly constant over all test periods/ conditions. The auxiliary cooler also requires ~1 KW of electric power to run, which is not accounted for in Table 1.

Generally, higher ratios (more water for less fuel) are observed on days when the relative humidity is above ~40%, and where the relative difference between humidity and temperature values is minimized (i.e. high humidity, high temp, moderate humidity, moderate temp), although the relationship is not linear. The least efficient ratio was observed on days in which ambient air temperature was very high (~120 degrees F) and RH was very low (below 40%). Conversely, there is a suggestion that when air temperature and humidity are both very high, as on 31 July, then the unit operates most efficiently. This is one data point, and so should be treated with caution, but see also Gido et al, (2015) who concluded that for this reason, efficient year-round operation of an AWG is only practical in tropical areas with consistently high humidity and stable temperatures (p. 159). It is most accurate to state that the individual associations between temperature and RH and water production are non-linear, with some evidence that extreme divergence between temperature and humidity can decrease the efficiency of the system.

Conductivity tests were performed on product and condensate (pre filtered) water samples several times per day. Two samples per day were also drawn from the product water and sent to ATC chemistry lab to analyze PH and Total Organic Carbon (TOC). Product conductivity measurements taken early in the day were found to be relatively high (180 to 850 uS/cm), and then gradually decreased through the day to (35 to 90 uS/cm by the end of the day). Since condensate sampling was consistently low (15-30 uS/cm) the variation in product water conductivity was attributed to the Biostone filtration systems altering the source water. Initial TOC samples revealed very high levels (>34ppm). Isolating engine and fuel burner exhaust and diverting these from the air intake on the unit reduced TOC to an average of 1.45 ppm/ mg/L in product water, which meets EPA's 2mg/L standard. The majority of the ATC pH test results were below the minimum recommendation of five units per TB MED 577.

See Table 2 below for a more detailed breakdown of water quality results.

*Table 2. Water quality results**

CONSTITUENT	LIMIT: STANDARD[a] (MAXIMUM ACCEPTABLE)	LIMIT: TEST METHOD REPORTING	WATER: PRODUCT, 06 14 JUL	WATER: PRODUCT, 06 27 SEP	WATER: CONDENSATE, 06 14 JUL	WATER: CONDENSATE, 06 27 SEP
Color	50 units	1 unit	BRL	BRL	BRL	BRL
Turbidity	5 NTU	0.1 NTU	8.66 NTU	0.23 NTU	0.78 NTU	0.46 NTU
Arsenic	0.2 mg/L	4 ug/L	BRL	BRL	BRL	BRL
Chloride (Cl)	600.0 mg/L	1 mg/L	BRL	BRL	BRL	BRL
Cyanide (CN)	2.0 mg/L	0.00641 mg/L	BRL	BRL	BRL	BRL
Mg	150.0 mg/L	0.2 mg/L	1.86 mg/L	BRL	1.57 mg/L	BRL
pH	5.0-9.0 units	1 unit	6.69 units	6.66 units	5.04 units	6.59 units
Sulfate	400.0 mg/L	1 mg/L	29.7 mg/L	8.5 mg/L	5.11 mg/L	2.2 mg/L
TDS	1500.0 mg/L	1 mg/L	56 mg/L	14 mg/L	24 mg/L	6 mg/L
Total coliform	1.0 per 100 mL	1.1	BRL	BRL	BRL	-
TOC	2 ppm[b]	0.5 mg/L	29 mg/L	1.7 mg/L	35 mg/L	3.3 mg/L

*Courtesy of TARDEC: ATEC PROJECT NO. 2006-DT-ATC-FCSOS-D1766. REPORT NO. ATC-9343

Conclusions. The TARDEC evaluation covers water production and fuel efficiency, as well as water quality and so is well aligned to EPA's mission/ interests in this technology. Even at optimal operating conditions, fuel/ water ratios ~4 gallons of water/ gallon of diesel suggest that AWG is fairly inefficient compared to alternative technologies such as reverse osmosis (RO) used in desalinization, which typically achieves water/fuel ratios of between 0.0035-0.0055 kWh/L of water produced, which translates to about 2800 gallons of water/ gallon of diesel fuel at the lower end. It should be noted that

RO is typically a large-scale technology producing 10's of millions of gallons per day and therefore this comparison to AWG is intended for illustrative purposes only.

Despite the limitations of current off the shelf solutions, recent advancements in hygroscopic materials and vapor compressions technology merit further consideration of the viability of AWG by EPA/ ORD. In particular, ORD sees a need for further evaluation of microbial growth on condensation coils against drinking water standards, as well as systems-based evaluation of AWG cost and performance in small scale applications, such as expanding the availability of water during shortages, contamination events and other interruptions of service. This would include scenario-based evaluation and testing in real-world conditions. This work could be performed through direct collaborative agreements with AWG manufacturers, or working alongside other federal partners, such as TARDEC, who have ongoing testing programs for AWG technology. ORD is currently developing plans in both of these areas as detailed in the section that follows.

Project Objectives and Rationale

1) **Assess quality of product and condensate water of systems from commercial collaborators:** Given the nature of atmospheric water generation, high quality produced water is anticipated; however, it may not be safe for human consumption. Concentrating large volumes of air can simultaneously concentrate contaminants, and microbial growth in plumbing and stored water is possible (Wahlgren et al. 2001). The primary human health concern is opportunistic pathogens, such as Legionella spp. and Mycobacterium spp., that are commonly associated with drinking water infrastructure. While data on the microbial risks associated with atmospheric water generators are unavailable, air-handling units (i.e., large air conditioning units) are operationally similar and may provide insight on condensate quality. Glawe et al. (2016) analyzed air-handling unit condensate from a diverse set of commercial buildings for physical properties, chemical contaminants, metals, microbial indicators, and pathogens. Although pathogens were not detected in the study, frequent detections of heterotrophic and coliform bacteria, as well as eukaryotic cells, indicate the potential for hazardous conditions to develop (Glawe et al. 2016). Additional studies have demonstrated the deposition of microorganisms to *condensation surfaces (Wu et al. 2016) and reported condensate to contain 105-107 CFU bacteria per mL (Hugenholtz and Fuerst 1992). Other reports have directly detected opportunistic pathogens such as Legionella spp. in condensate water (e.g., Alipour et al. 2013). These results suggest that atmospheric condensation systems, including water generators, are subject to microbial contamination and may thus present human health risks. A comprehensive evaluation of the microbial quality of condensate and produced water is therefore necessary to ensure the safe implementation of atmospheric water generation technology. Condensate and produced water samples from AWGs provided by collaborating commercial vendors will be analyzed by ORD using cultivation-based and molecular methods (qPCR) to detect and quantify organisms of these species. In addition, next-generation sequencing (metagenomics) will be used to identify any additional risks and to compare the microbial community to that occurring in other water sources. Standard water quality parameters (*e.g.*, pH, conductivity, total dissolved solids, heterotrophic plate counts) will be monitored to ensure suitability of produced water for potable and non-potable applications.

Project objectives 1 and 2 require engagement of commercial partners. A separate document decribes a more detailed statement of work (SOW) for Collaborative Agreement for Research and Development (CRADA) with companies.

2) **Construct scenarios and perform LCA analysis of systems from commercial collaborators:** Holistic approaches such as comparative life cycle assessment (LCA) and life cycle costing (LCC) provide tools to measure the trade-offs involved in various AWG scenarios and the opportunity to optimize cost/ benefits. The aim is to assess not only the ideal conditions and "best case' potential for the technology in terms of water production, but also to assess the economics and resource impacts of procuring, deploying, and operating the device under different conditions and for different purposes. Like other drinking water treatment technologies, energy consumption is the driving force in the long term viability of AWG applications. Available AWG research has reported energy consumption ranging from 0.31 to 0.63 kWh/L water produced (Gido et al., 2016a). However, the energy reported often refers to the direct electricity used to power the compression, heat exchanger, and other components in the systems, with or without the filtration or sterilization (Peters, et al., 2013). Other factors could play critical roles in the operation and viability of the technology such as the site specific climate (tropical/subtropical) (Gido et al., 2016b), meteorological condition (relative humidity, day/night time) (Gido et al., 2016b), the geographic location (transportation cost), local water sources, etc. Unit performance under these conditions merits more comprehensive evaluation. Two base scenarios are proposed, reflecting the use of AWG tech as a temporary and permanent water production solution (see Table3 below for more detail); these scenarios are provided to initiate discussions and are not considered final. The LCA results will allow stakeholders such as disaster planners, federal state and Municipal officials, and utility operators to better understand the costs and benefits of operating a vapor pressure AWG compared to alternative solutions. On a more scientific level, these results will help define current limits of technology for specific. applications of interest, and highlight priority areas for future research and development with key partners, including TARDEC. Comparisons with other alternative innovative emerging technologies on a consistent economic basis will provide valuable quantified contrasts, predict most cost-effective solutions, and offer more in-depth evaluations than are currently available in the research literature.

Table 3. Base scenarios for LCA evaluation

Scenario 1: Temporary/decentralization/mobile concept	**Rationale 1**	**Rationale 2**	**Objectives**
AWG vs Membrane Bioreactor (MBR)	As water resource becomes scarce and the financial burden of large piping and pumping infrastructure, decentralized concepts have been explored in urban settings.	During disaster relief efforts, the availability of clean drinking water is often critical, a mobile purification system for potable water would provide reliable temporary water supply.	To evaluate the life cycle costs and cumulative energy demand of the two technologies to achieve the same point of entry treatment
AWG vs bottled water	When emergency happens that water supply is not available, often bottled water is the option to provide potable water		To evaluate the life cycle costs and cumulative energy demand of the two options, take into account of the transportation and material inputs in bottled water
Scenario 2: Permanent concept/alternative water source/superfund remediation sites	**Rationale 1**	**Rationale 2**	**Objectives**
AWG vs reverse osmosis (RO)	Desalinization has become increasing cost-effective, yet energy requirement may still be high. In the coastal region, more favorable conditions might exist for the application of AWG		To evaluate the life cycle costs and cumulative energy demand of the two options, take into account of the waste disposal processes etc.
AWG vs contaminated source water (PCE dichlorination)	When superfund site involves remedial actions, an alternative water supply is often required. The treatment of contaminated source water is often not economically feasible		To evaluate the life cycle costs and cumulative energy demand of the two treatment trains, to achieve the same water quality

3) Advancing AWG in partnership with TARDEC

EPA Office of Research and Development (ORD) and the Department of Defense renewed a Memorandum of Understanding (MOU) in January 2017 for the purpose of collaborative research, development, and tech demonstration to support shared EPA and DoD resource security and resilience goals.

As discussed in the previous section, the US Army's Tank Automotive Research Development and Engineering Center (TARDEC) program, have been engaged in testing Atmospheric Water Generation (AWG) systems since 2006. Recently, TARDEC began developing new plans for development, prototyping and testing of an advanced vapor compression water maker with an integral high efficiency generator built by Rocky Research that could represent a significant advancement in fuel efficiency and production capacity compared to currently available AWG tech. The new TARDEC work will begin in 2018.

ORD proposes to collaborate concurrently with TARDEC on the Rocky Research system to A) assess the water quality of product water, in particular microbial growth on condensation coils and in product water, and B) to create and evaluate scenarios for the most efficient use of the Rocky Research system or similar technology. All costs for procurement and installation of the Rocky Research system will be met by TARDEC. EPA will provide financial and staff resources to cover the costs of the activities outlined below.

Specific Research Questions:

Component 1) Assess quality of product and condensate water:

- What is the water quality of AWG condensate?
- Is AWG condensate water safe for potable and non-potable use?
- What type of microbial community forms in AWG biofilms?

Component 2) Construct scenarios and perform LCA analysis of Rocky Research system and similarly spec'd units

- What is the life cycle cost and cumulative energy demand of AWG systems under different application scenarios?
- How do AWG systems perform in comparison with other innovative technologies under the same scenarios?
- Can integrated assessment metrics such as LCA and LCC be used to provide holistic framework in evaluating innovative technologies?

Resource Overview (TBD)

[TBD]

on site, data management, data analysis, or reporting.

Proposed Project Team

[Fill in details here]

Proposed Project Schedule

[TBD]

Deliverables

Reports, scientific publications, and data on water quality analysis

Reports, scientific publications, and data on scenarios and LCA analysis

References

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